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Science Applications International Corporation (SAIC) is testing a semi-empirical signal processing approach to estimate the yield of explosions. Under Air Force Research Laboratory contract FA8718-05-C-0019, SAIC developed a technique to combine the 'truth' of empirical observation with the flexibility of synthetics to generate 'empirical filters' that can be applied to the synthetic seismogram. Specifically, our approach is to design filters that transform the synthetic waveforms to match observed referenced waveforms. In the current project, the technique has been modified (and tuned) to provide yield estimates of interesting events. In particular, estimates of the yield of the North Korean Nuclear Test of Oct. 9, 2006, will be presented. The approach used is to compute semi-empirical synthetic waveforms based on a reference event, then use those synthetics to determine the appropriate scaling (yield) of the event of interest. The semi-empirical synthetics are created by computing a full waveform synthetic to the reference event then determining a filter that transforms the synthetic to the observed data, which is then applied to the new event. The empirical correction should include many of the non-modeled complexities information, particularly if the reference and new events are nearly co-located. As the North Korea event occurred in a seismically isolated region with no nearby earthquakes, more distant events must be used. An active source experiment for wide-angle reflection and refraction near the border in China provides some sort of propagation calibration. While the yield from the China experiment was small (1.2–1.5 tons), a good signal was recorded at the station MDJ for one particular explosion. This event, roughly ½ way between the North Korean Nuclear Explosion and MDJ, provides our reference event for our yield estimate of the North Korean Nuclear Explosion. In addition to computing the yield for the explosion, which we compute to be 850 tons (with an uncertainty of about 100 tons), we explore tradeoffs between the estimated yield and the assumed source depth of the nuclear explosions, the impact of variations of propagation models on the results, as well as yield vs. frequency.

Preliminary analysis indicates that the apparent yield does not vary significantly with the velocity model, but is highly dependent on the attenuation structure (Q), that the apparent yield increases significantly with depth (due to surface wave excitation) at lower frequencies, and higher frequencies produce a lower, but more stable yield estimate than the broad-band solutions.

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SEMI-EMPIRICAL YIELD ESTIMATES FOR THE 2006 NORTH KOREAN EXPLOSION

David H. Salzberg

Science Applications International Corporation

Sponsored by Air Force Research Laboratory

Contract number FA8718-08-C-0011

Proposal No. BAA08-60

**ABSTRACT**

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## **OBJECTIVES**

The objective of this project is to use and extend SAIC's semi-empirical synthetic approach [Salzberg, 2005] to facilitate a proof of concept demonstration on yield estimation. While SAIC was able to estimate the yield of the North Korea Test of Oct. 6, 2006 to be about 460 tons, the accuracy of the estimate is unknown. In particular, the variability caused by uncertainty in the crustal model is explored. In addition, in the future, we will apply the technique to events with known yields, providing an understanding of the error bounds of estimates based on this approach.

## **RESEARCH ACCOMPLISHED**

### **Yield estimate for North Korea**

We have used a slight modification of our semi-empirical synthetic seismogram method of Salzberg [2005] to estimate the yield of the North Korea Nuclear test of Oct 9, 2006. The data used for the processing is from the seismic station, MDJ, which is located in Northeastern china, as shown in Figure 1. The reference data, used for calibration, was from a wide-angle refraction experiment. The 1.2–1.5-ton shot was set off 190 km south of MDJ, or about ½ way between the North Korean test and MDJ. While the data for the Chinese reference event is noisy, at higher frequencies bands, (> 1 Hz), the signal is clear (Figure 2). The signal for the North Korea Nuclear test has significant signal at all frequencies (Figures 3 and 4).

### **Method**

The approach is to compute a semi-empirical synthetic, which is expressed as:

$$new(\omega) = \frac{reference(\omega)}{synthetic_{reference}(\omega)} \cdot synthetic_{new}(\omega) \quad (1)$$

where *reference* and *new* refer to the observed waveforms, and *synthetic* refers to the synthetic waveform computed for a specific event range, depth, and mechanism. Thus, as we know the location of the nuclear and chemical explosions, the mechanism (assumed to be isotropic explosion), and the yield for the chemical shot, the formulation can be re-written to:

$$new(\omega) = \frac{reference(\omega)}{synthetic_{reference}(\omega) \cdot yield_{reference}} \cdot synthetic_{new}(\omega) \cdot yield_{new}, \quad (2)$$

where the synthetics are computed for the same yield.

### **Application**

As the separation between the reference event (Chinese experiment) and the North Korean explosion was significant (190 km, or ½ of the propagation distance, shown in Figure 1), and the frequency content of the data required high-frequency (>5 Hz) analysis, a coherent comparison was not feasible. Instead, the yield will be estimated by integrating (or summing) the energy envelopes, which is represented as:

$$Yield_{NK} = Yield_{CN} \cdot \frac{\sum O_{NK}}{\sum O_{CN}} \cdot \frac{\sum S_{CN}}{\sum S_{NK}} \quad (3)$$

where  $O$  is the energy envelope for the observations of the two events,  $S$  is the energy envelope of the synthetics for the two events, the subscript  $NK$  refers to the North Korean test, and  $CN$  refers to the China experiment.

The primary issue that needs to be addressed is the background noise level in the Chinese reference event. The approach used is a Savitzky-Golay smoothing filter (Orfanidis, 1996) to characterize the noise. This technique is designed to remove impulsive noise from a narrow-band continuous signal. In our application, the narrow-band signal is the microseismic noise, and the impulse is our signal. So, the smoothing filter is designed to mimic the microseismic noise without perturbing the impulsive event signal.

The noise is then subtracted from the observed waveform for further processing. The results, shown in Figure 5, indicate that this approach can be used to minimize the longer period noise. The reduced long-period noise will allow for the processing at longer periods, as shown in Figure 6.

### Data Analysis

The approach to analyzing the received energy in the signal is to sum the energy envelopes. The response is analyzed in a frequency dependent fashion by high-pass filtering the data with a varying corner frequency. The energy envelope is computed by:

$$A(t) = |s(t) + iH(s(t))| \quad (4)$$

where  $A$  is the energy envelope,  $s$  is the observed seismogram,  $H$  is the Hilbert transform, and  $||$  is the absolute value.

The computation is shown in Figure 7; first, the energy envelope is computed. Then, the remaining noise is estimated (based on the pre-signal energy). The background noise is then subtracted from the energy estimate. The remaining signal is the observed energy from the event. This process is repeated for frequencies ranging from 0.1 to 5.0 Hz, with the results shown (for both the data and synthetics) in Figure 8.

### Computation of the Synthetic Seismograms

Synthetic seismograms were computed using Herrmann's (2002) wavenumber integration software with a sample rate of 20 Hz to match the data at MDJ. Three velocity models were used: the first model was an arbitrary highly attenuating low-velocity model, the second was based on Herrmann's (2005) model for the Korean Peninsula, and the third model modified Herrmann's model to increase the attenuation in the shallowest layer to simulate Rg scattering. Qualitatively, all of the models produce more surface-waves than the observed signal. The basin model shows a classic dispersive chirp of about 45 seconds, whereas the high-Q version of the Herrmann model shows an unrealistically large Rg phase (Figure 9). Modifying the attenuation to account for scattering of the Rg (due to the tomography shown in Figure 1) gives a more realistic looking synthetic, again shown in Figure 9.

### Yield Estimates

The sum of the energy envelopes is then computed in a manner identical to that performed on the data. Thus, for each model, we have measured all of the terms in the sum in the equation below.

$$Yield_{NK} = Yield_{CN} \cdot \frac{\sum O_{NK}}{\sum O_{CN}} \cdot \frac{\sum S_{CN}}{\sum S_{NK}} \quad (5)$$

The yields can be estimated using each model. The basin model shows a yield of about 900 tons at shallow depths and frequencies, increasing significantly at source depths below 2 km (which is the depth of the shallowest layer). The high-Q Herrmann model shows a very large yield at low frequencies, corresponding to the extremely large Rg phase observed. At higher frequencies, the yield is estimated to be about 1 kt. The low-Q Herrmann model (which is the preferred model) gives a yield of about 850 tons, with smaller variations (less than 100 tons), and is shown in Figure 10. It is worth noting that the corner frequency for both the reference event and the nuclear event are above the Nyquist frequency.



## CONCLUSIONS AND RECOMMENDATIONS

We have demonstrated that the semi-empirical technique seems to produce stable estimates of the yield of the North Korean explosion, provided a reasonable estimate of the attenuation is used. Even with unreasonable  $Q$ 's, the yield apparently only varies by about 20% (850 tons to 1 kt).

## ACKNOWLEDGEMENTS

Discussions with Jesse Bonner were useful in characterizing both the corner frequency of the explosions and the appropriate value of  $Q$  for Herrmann's model. In addition, Michael Pasyanos recommended the use of Herrmann's (2005) model.

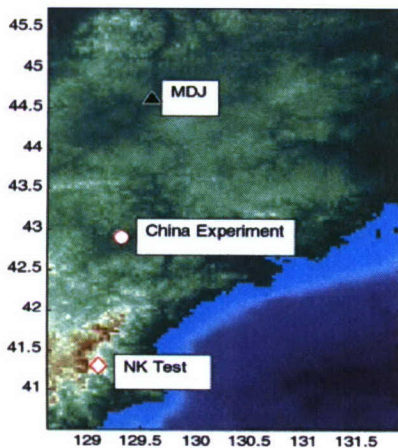
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Herrmann, R. B. (2002). *Computer Programs in Seismology*, St. Louis University.

Herrmann, R. B., Y. S. Jeon, J. Yoo, K. H. Sho, W. R. Walter, and M. Pasyanos (2005) Seismic Source and Path Calibration in the Korean Peninsula, Yellow Sea, and North East China, in *Proceedings of the 27<sup>th</sup> Seismic Research Review: Ground-Based Nuclear Explosion Monitoring Technologies*, LA-UR-05-6407, Vol. 1, pp. 42–51.

Orfanidis, S. J. (1996). *Introduction to Signal Processing*, Prentice-Hall, Englewood Cliffs, NJ, 1996.

Salzberg, D. H., K. E. Votaw, and M. E. Marshall (2005). Seismic source locations and parameters for sparse networks by matching observed seismograms to semi-empirical synthetic seismograms, in *Proceedings of the 27<sup>th</sup> Seismic Research Review: Ground-Based Nuclear Explosion Monitoring Technologies* LA-UR-05-6407, Vol. 1, pp. 454–462.



**Figure 1: A map showing the relative locations of the North Korea test, the China experiment, and the seismic station MDJ.**

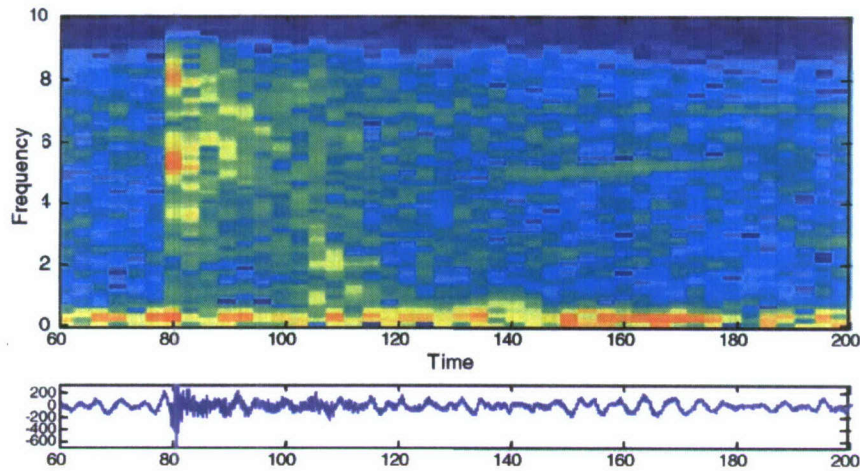


Figure 2: Unprocessed waveform and spectrogram for the waveform from a wide-angle refraction/reflection experiment in North Eastern China. (1.2-1.5 t). This event is used as a reference event.

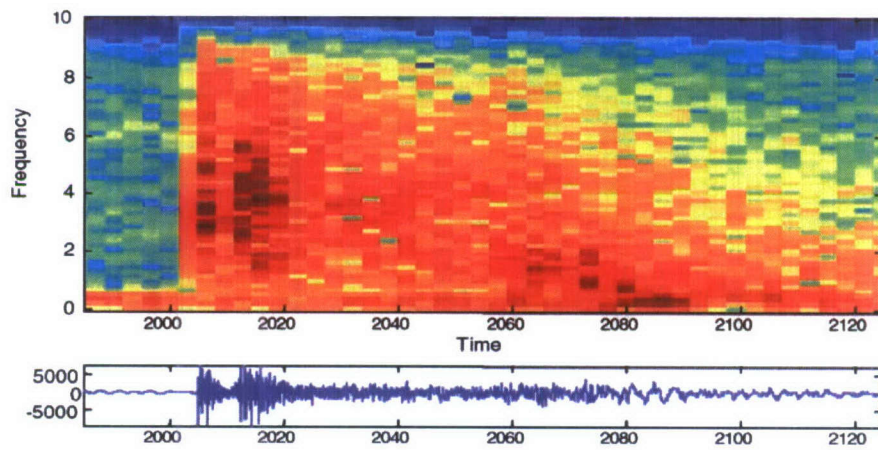


Figure 3: Unprocessed waveform and spectrogram for the North Korean nuclear test.

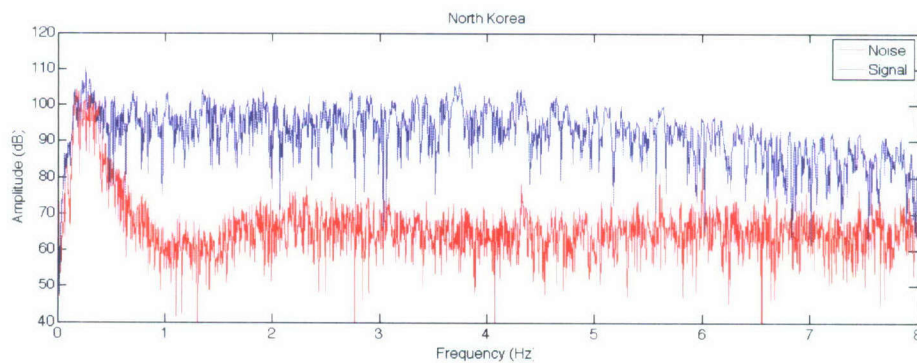
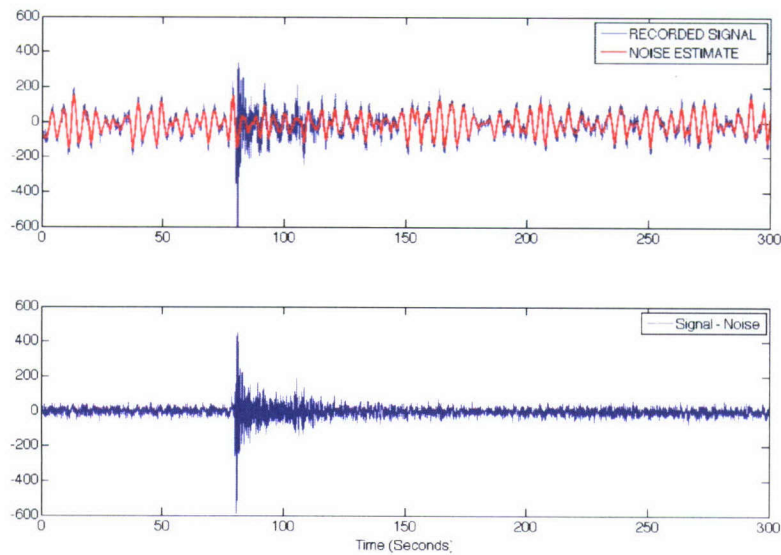
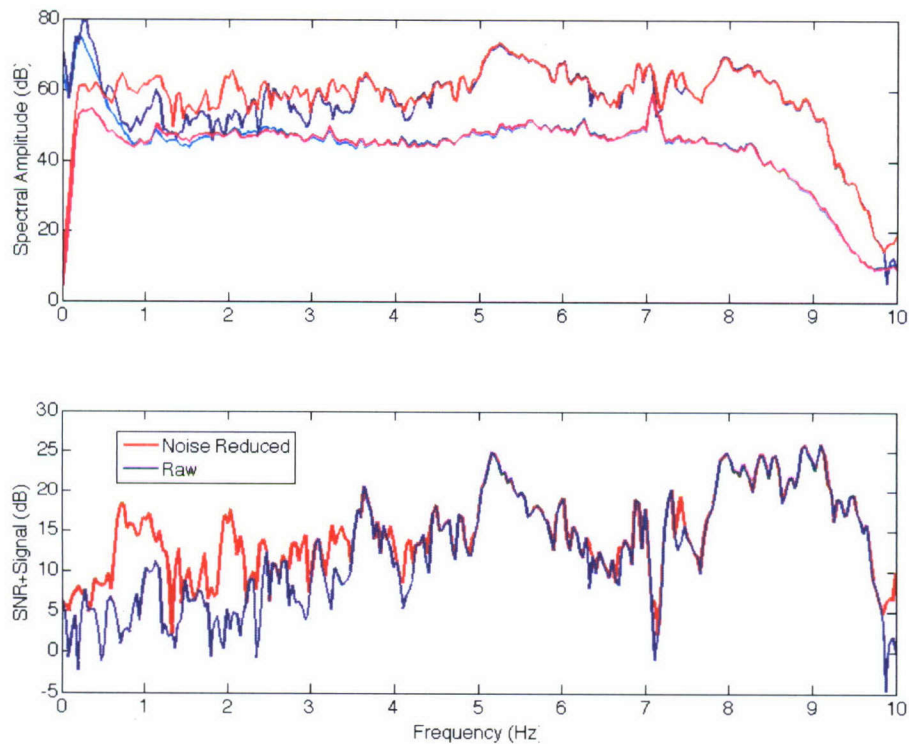


Figure 4: Signal-to-noise ration for the North Korean Explosion recorded at MDJ.

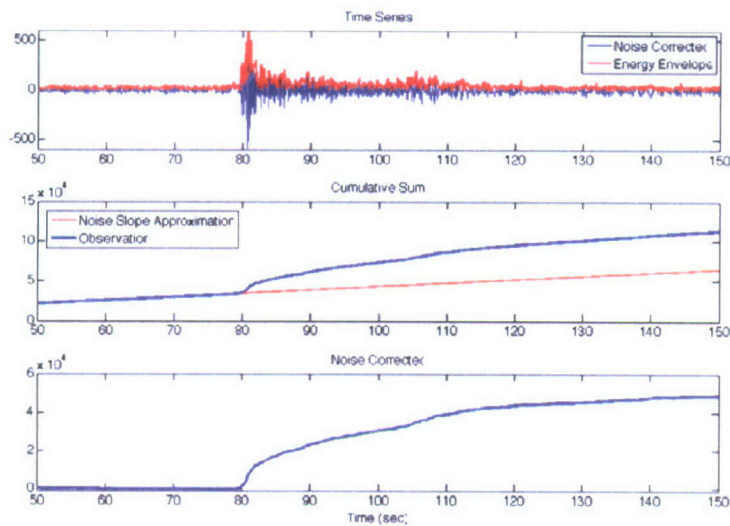


**Figure 5: Noise estimation (top) from the Savitzky-Golay smoothing filter, and the noise-reduced data (bottom).**

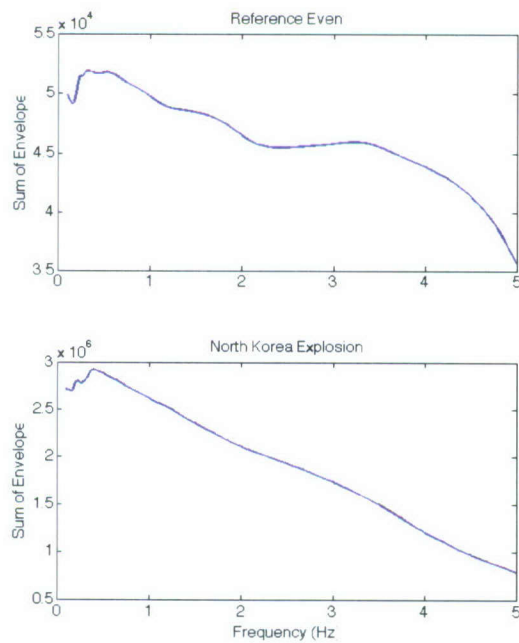


**Figure 6: The top shows a comparison of the signal and noise of the raw data (blue) and original noise (cyan) and the noise-reduced signal (red) and noise (magenta). The bottom figure shows the sifting SNR between the original and noise-reduced. The primary difference is the noise-reduced signal is clear down to ½ of a Hz, whereas the original is useful at frequencies about 3 Hz.**



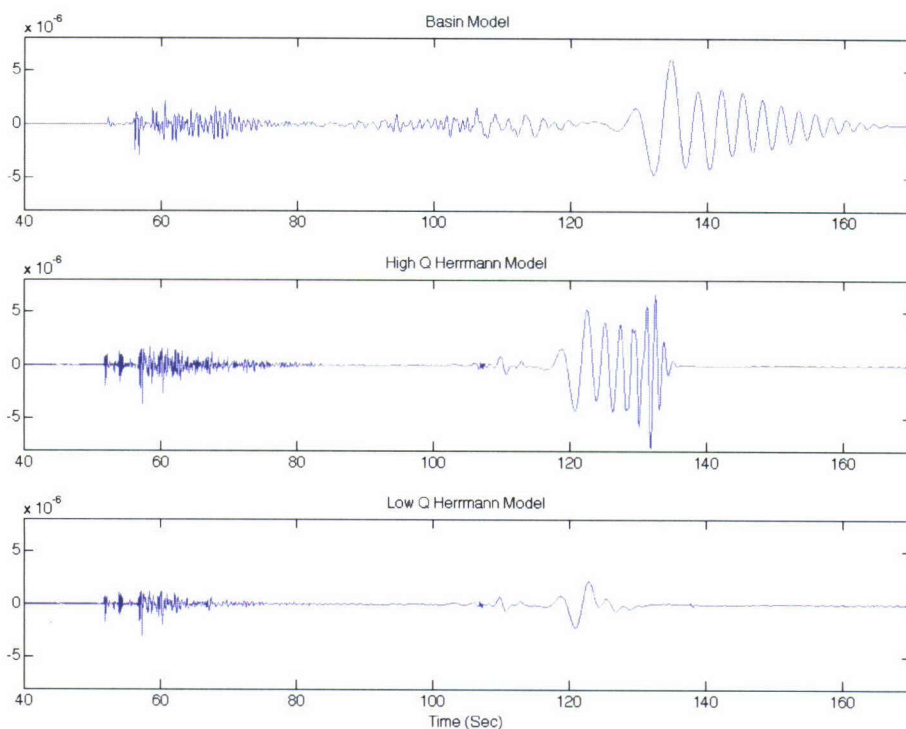


**Figure 7: The approach to computing the total received energy. First, the noise-corrected data is filtered then converted to energy envelope (top). Next, envelope is summed. The pre-signal sum gives us an approximation of the remaining noise (middle). The Pre-signal noise is then subtracted from the curve to give the received signal (bottom).**

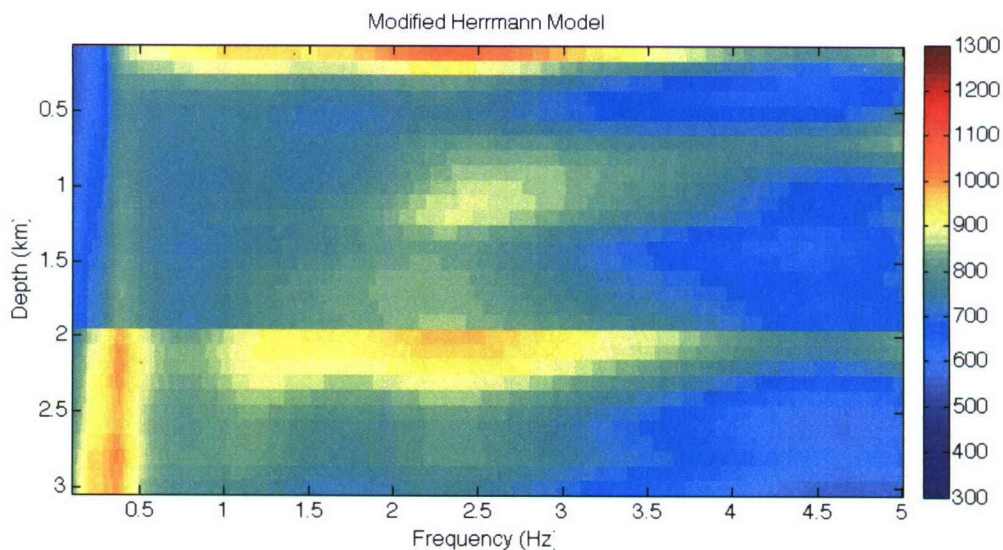


**Figure 8: The sum of the energy envelopes of the reference event (top) and the North Korean explosion (bottom).**





**Figure 9: Comparison of the synthetic for 800 m depth for the three velocity models.**



**Figure 10: Yield versus frequency and depth for our best model. This model is based on Herrmann's [2005] model as simplified and verified by LLNL. The model is modified to increase the attenuation (decrease the Q) to accurately reflect the scattering of  $R_g$ , as recommended by Bonner (personal communication). The results show that the probable yield 850 tons with an uncertainty of about 100 tons.**